TSUNAMI DETECTION: ANALYSIS OF GPS DATA FROM A BUOY ANCHORED OFF THE MUROTO PENINSULA, IN JAPAN, DURING THE EVENTS OF SEPTEMBER 5-6, 2004

Oscar L. Colombo, August 2005.

On September 5 and 6 2004, there were several submarine seismic events off the Kii Peninsula, centered on a region about 300 km south of the city of Nagoya. Two of these events went on to produce tsunami waves, in places as high as one meter on reaching the coast (details, in page 3). A buoy with a GPS receiver, especially designed for detecting tsunami, was undergoing tests offshore of Shikoku Island, some 13 km from the Muroto Promontory, and 200 km south of the city of Osaka (Figs. 2, and 3a-b). The buoy's GPS data, differenced with that of a base station in Muroto, were used successfully to sense, in real time, the tsunami waves as they went by, even though these were only 15cm high, at that point. Ordinary waves as high as 4 m were filtered out digitally, taking advantage of their much shorter periods (rarely more than 15 seconds, compared to 10-15 minutes -- in this case). The GPS results agreed with both the tidal record from a gauge near Muroto (Figs. 2 and 10), where they arrived some 12 minutes later, and with the waves computed using a tsunami model (Fig. 1). Similar results were obtained relative to a GPS site in Osaka, by Dr. Terada and colleagues at Hitachi Zosen (Kato et al, 2005).
The buoy GPS tsunami meter is the result of a cooperative effort between Tokyo University and Hitachi, under the leadership of Prof. Teruyuki Kato and of Dr. Yukihiro Terada, respectively. Recently, the system has moved on from the experimental to the operational phase, to become a new kind of sensor in Japan's tsunami warning system.

The main challenge, now, is to detect tsunami with buoys placed much farther from shore, so as to give much earlier warning to the coastal populations likely to be affected. Long-baseline GPS solutions are intrinsically less precise than short-baseline ones. The author has been invited by his Japanese colleagues to collaborate on developing methods for detecting tsunami using GPS on buoys; in this report he presents his results so far.

To understand better how to get reliable and sensitive early tsunami detection, the GPS data have been processed with a precise, very long-baseline differential GPS positioning technique, using dual-frequency carrier phase with floated ambiguities, implemented in the author's "IT" software. Also investigated: the possible use of the precise point positioning method, also implemented in "IT" (Colombo et al., 2004). With this method, only data from the buoy's receiver is needed, along with precise estimates of GPS satellite orbits and clocks. Base reference stations are not used, making the distance from land irrelevant. This method is becoming rapidly adopted in routine, turn-key operations, for a wide variety of applications; it is unclear

whether its usual precision, at present, is adequate for the delicate task of detecting small, but dangerous, tsunami waves in the deep ocean.

Most of the accompanying plots and pictures are self-explanatory: the information needed to understand them can be found in their headers, text boxes, and captions underneath each. What follows will deal only with those figures that show the results of the data analysis itself.

The author's results, with either the short baseline Muroto - buoy (Fig. 11), or the long baseline Osaka - buoy (Fig. 12), are virtually identical for the major tsunami event. This one took place just after the midnight of 6 September 2004, Japan Standard Time (JST), or UTC+9hs. (Epochs are given in GPS time, or UTC+13s.) Figure 13 shows the result of using the point positioning technique. Some differences between this and the differential results are noticeable, particularly between 16:55hs and 17:00hs UTC.

All three plots agree quite well, most of the time, with those obtained for the short-baseline Muroto - buoy by Terada and colleagues (the two curves at the bottom of Fig. 10). The greatest difference can be seen at the start of the first of the main tsunami waves, around 0:25hs JST (or 15:25hs UTC, or 15.42hs in the plot). The wave's rise in Figs. 11-13, is steeper and higher than in Fig. 10. The reason is not clear, but could be related to problems with the processing of the GPS data. Different software may select and edit out satellite data differently. That the same feature appears in all three plots, with two different reference stations, and with none, seems to point to the processing of the buoy's data. This needs more study.

An earlier seismic event (page 3) resulted in substantial, though smaller, tsunami waves, as shown in the records of several tide gauges along the coast (Fig.2). Around the time when this happened, the signature of some very long period waves can be seen, clearly standing out from the background (Figs. 14-16). An even earlier train of small amplitude long-period waves, centered at 7:00hs GPS, is shown in Fig. 17. This does not correspond to any reported seismic activity or tsunami (e.g., in page 3), but it might be due to small amplitude long waves, also known as far infragavity waves (Fig. 18), often caused by distant storms (Rabinovich and Stephenson, 2004).

In conclusion: Results look promising for the early detection and warning of tsunami waves with GPS receivers on buoys anchored far from the coast. The point positioning technique, in particular, would be ideal for this, as there is no limit to how far the buoy can be from the coast—if it could be used in a way that is both sensitive and reliable. Already, detecting tsunami waves of little more than 10 cm in height has been shown to be feasible; to put this in perspective: the great Indian Ocean tsunami of December 2004 was some 50 cm high in the deep ocean, as measured from space with satellite altimetry. These thoughts must be tempered by the realization that post-processed results tend to be better than real-time ones. But, while more work is needed, a case has been made for considering buoys with GPS as part of a future global tsunami early-warning system based on a variety of sensors.

Text of a report in: http://www.jishin.go.jp/main/index-e.html
at the Web site of the Headquarters for Earthquake Research Promotion:
--

Seismic Activity Off-shore Southeast of the Kii Peninsula

--

On September 5, at 19:07 (JST) there was a M6.9 (preliminary) earthquake off-shore southeast of the Kii Peninsula (off-shore of the Kii Peninsula). This event had a maximum seismic intensity 5 Lower in Nara and Wakayama prefectures.
This earthquake caused a tsunami on the Pacific coast from the Izu islands to the Shikoku region, with tsunami heights of 0.5m in Kozushima and 0.3m in Irozaki, Owase, Kushimoto and Murotomisaki. Also, at 23:57 (JST) on the same day, there was a M7.4 (preliminary) earthquake off-shore southeast of the Kii Peninsula, to the east of the previous event (off-shore of Tokaido). This event had a maximum seismic intensity 5 Lower in Mie, Nara and Wakayama prefectures.
This earthquake caused a tsunami on the Pacific coast from the Izu islands to the Shikoku region, with tsunami heights of 0.9m in Kushimoto, 0.8m in Kozushima, 0.7m in Irozaki, 0.6m in Owase, and 0.5m in Murotomisaki. Including these events, there were 18 events with intensity equal to or greater than 1 by 14:00 (JST) on September 6. Those events were distributed about 100km southeast of the Kii Pennisula, near the Nankai Trough in an area that is approximately a 50 km square in size. Judging from the sequence of occurrence, it is thought that the seismic activity was a foreshock - main shock - aftershock sequence, with the event at 23:57 as the main shock. The focal mechanisms of the foreshock and the main shock showed reverse faults with compression axes in a N-S direction. It is thought that this event occurred within the Philippine Sea plate because the dip angle of the estimated fault plane is larger than that of the plate boundary between the continental and the Philippine Sea plates.

According to the GPS data, crustal movements toward the south ssociated with this event, were observed over a large area from Mie prefecture to Aichi prefecture (maximum displacements of approximately 4cm near the Shima Peninsula). This is consistent with the focal mechanisms of the current seismic activity.

These earthquakes occurred outside of the expected focal region of the so-called Tonankai earthquake, as evaluated by the Earthquake Research Committee, and the focal mechanisms are different than that of the expected Tonankai earthquake. So, it is thought that the current activity did not rupture the focal region of the expected Tonankai earthquake. Therefore, it is thought that this seismic activity does not have a direct affect on the expected Tonankai earthquake.
According to the long-term evaluation announced by the Earthquake Research Committee on September 27, 2001, there is an approximately 50 percent chance of occurrence of the expected Tonankai earthquake (approximately M8.1) within 30 years from January 1, 2001. In addition, there is an approximately 60 percent chance of occurrence within 30 years from September 1, 2004.

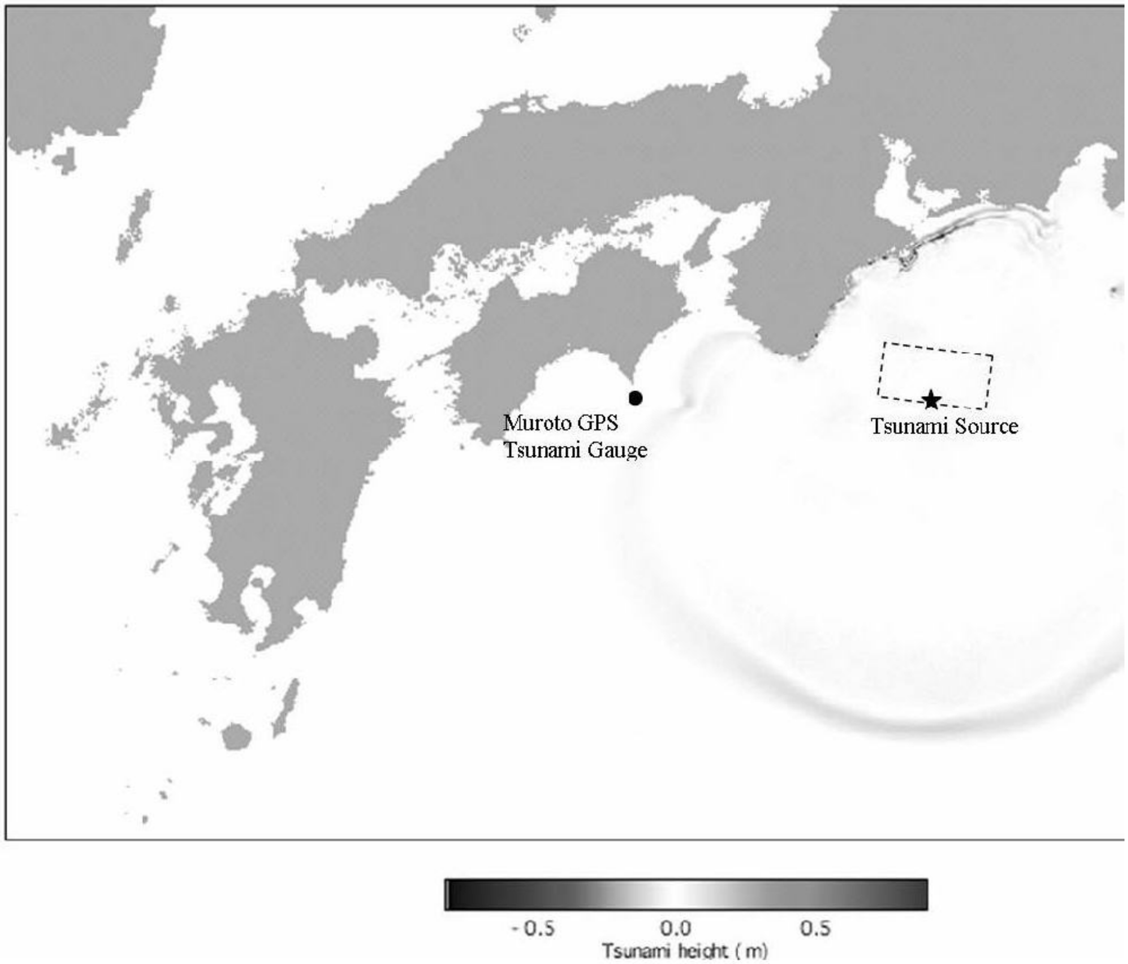

Figure 1: Tsunami waves caused by off-Kii Peninsula main shock of 6 September 2004, at 11:59 PM (JST), according to tsunami computer model.
(This, and Figs. 3a-b and 19, courtesy of Prof. T. Kato, Earth Research Institute, Tokyo University.)

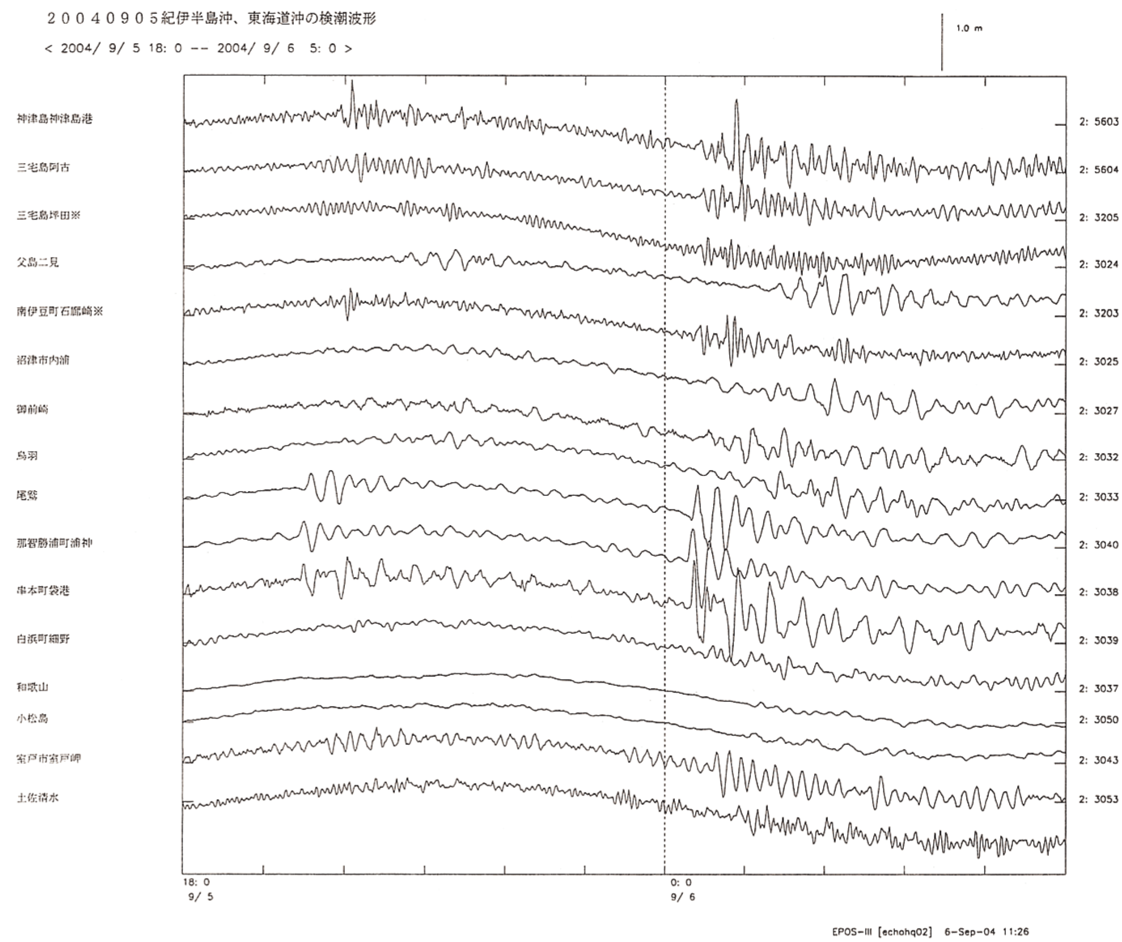

Figure 2: Tide gauge records, showing two tsunami waves at various locations, during 5-6 September 2005, following seismic events in that period. (From the Web site of the Headquarters for Earthquake Research Promotion; time and dates are Japan Standard Time, or JST.)

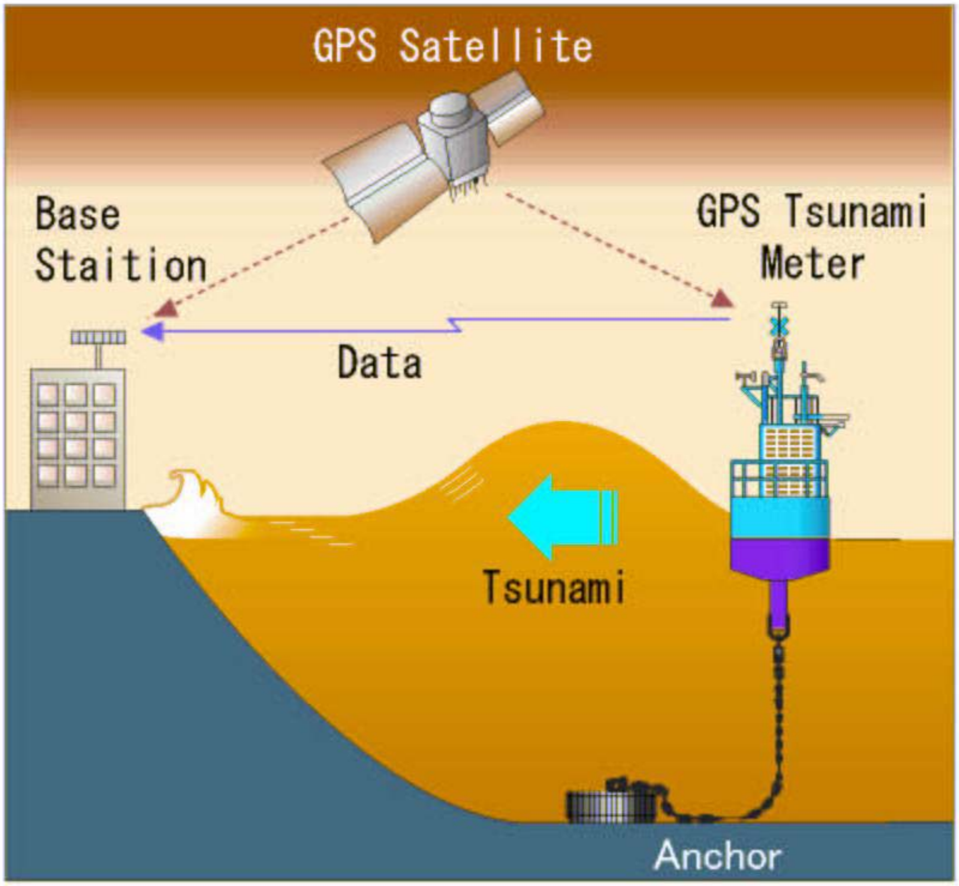

Figure 3a: Tsunami detection setup at Muroto. The distance between base station and buoy is 12.6 km, the ocean depth is 100m. (For more information, see: http://www.hitachizosen.co.jp/english/solution/ss/bousai/GPS_tsunami.pdf)

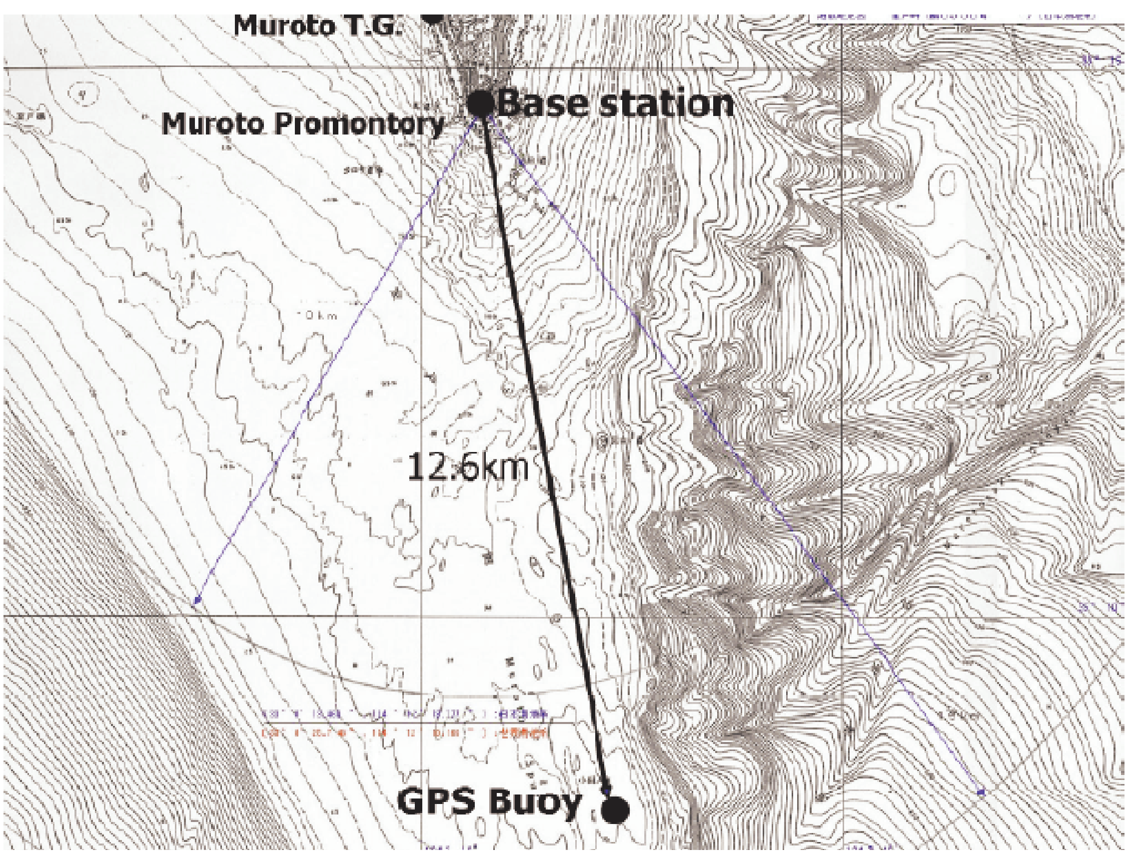

Figure 3b: Geographic locations of Buoy and Muroto Base Station.

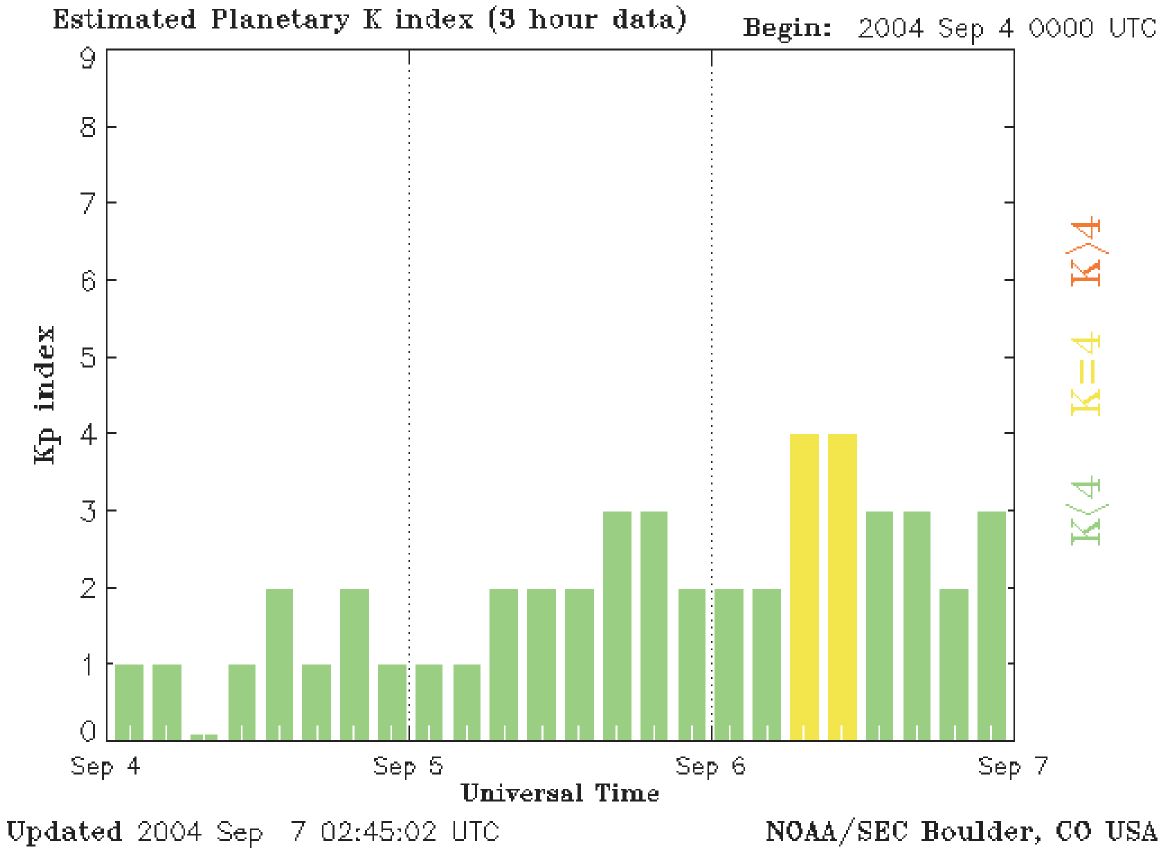

Figure 4: Geomagnetic activity during period of interest: Low, unlikely to affect adversely the propagation of GPS signals through the Earth's ionosphere.

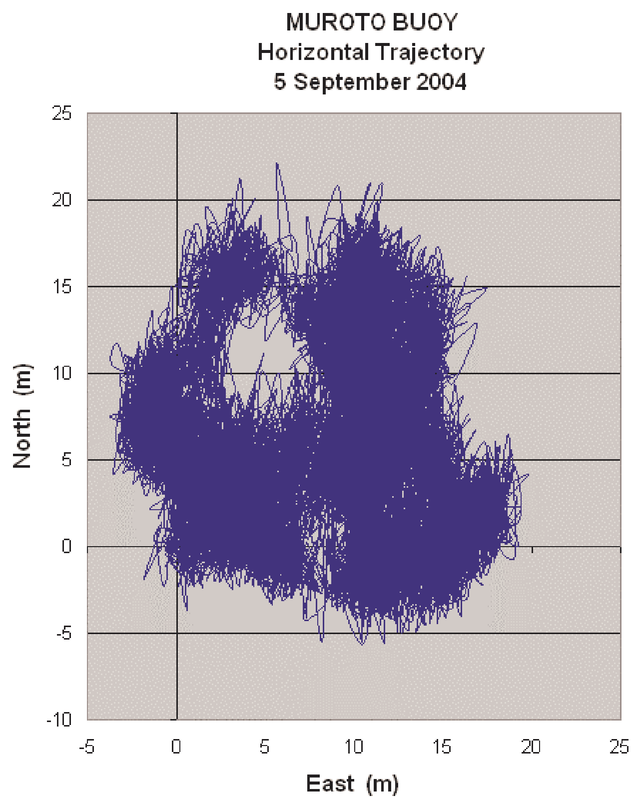

Figure 5: Buoy, horizontal track, 5 September 2004 (UTC)

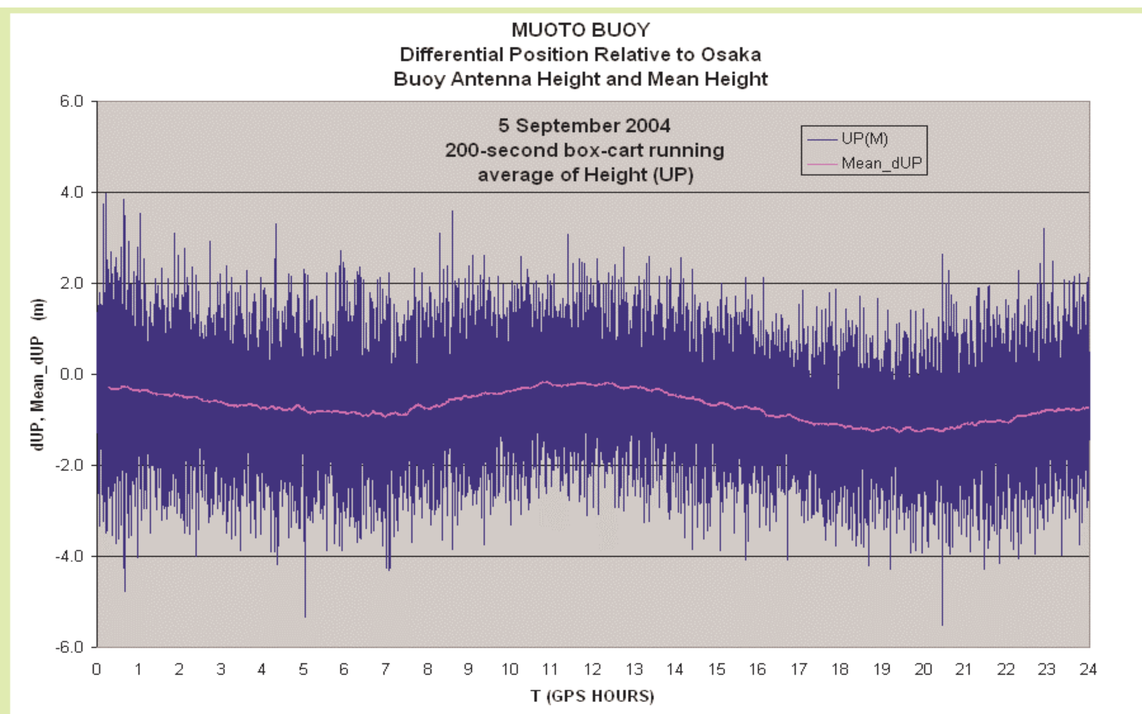

Figure 6: Buoy height changes, with up to 4 m waves, and moving average of height.

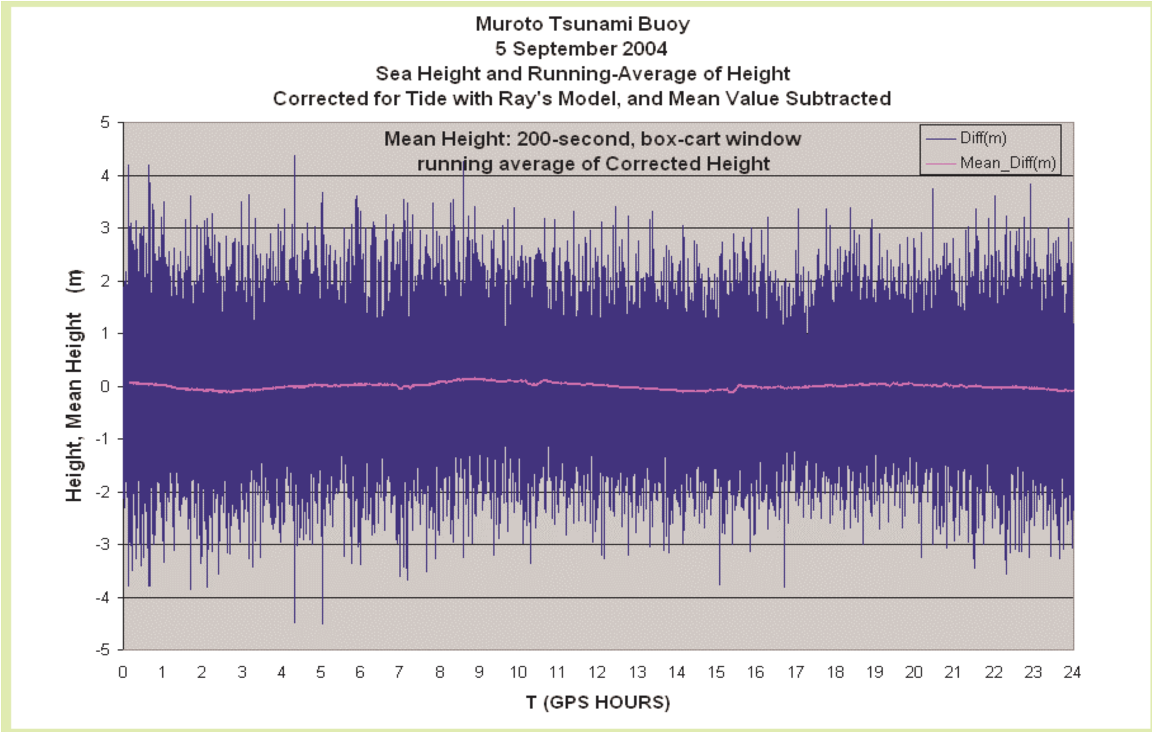

Figure 7: Same as Fig. 6, after subtracting the mean value, and also the ocean and solid earth tides.

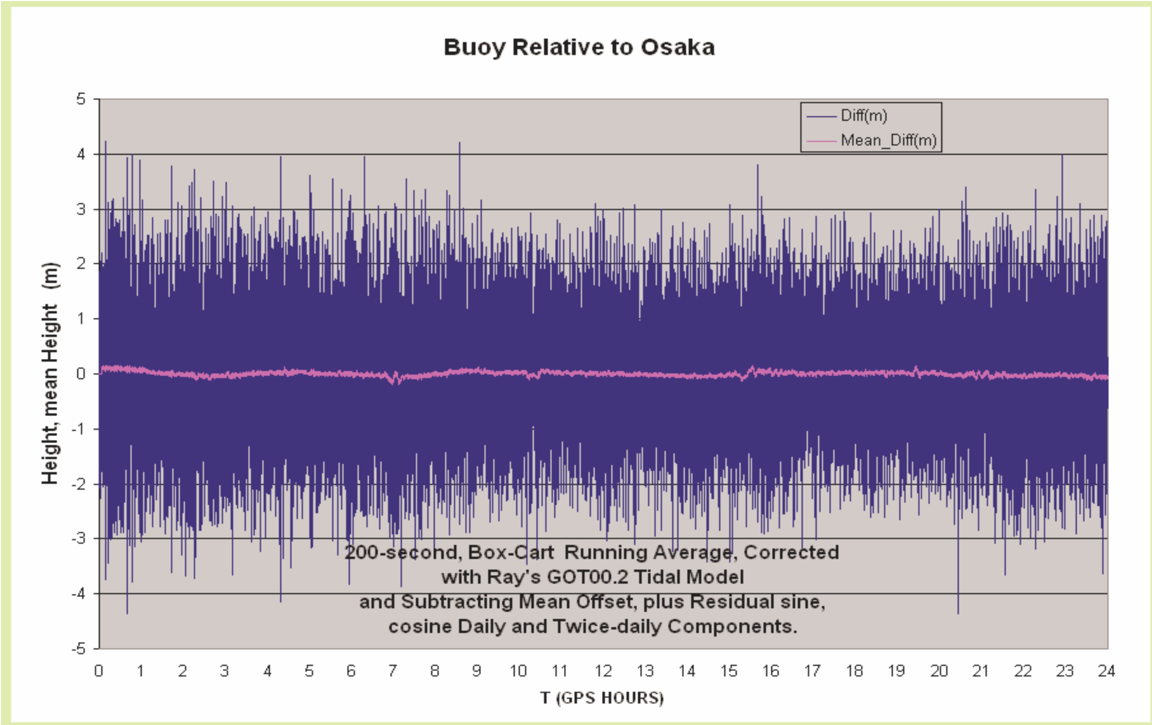

Figure 8: Same as Figs. 6 and 7, after further correction for small, residual once and twice-daily harmonic components.

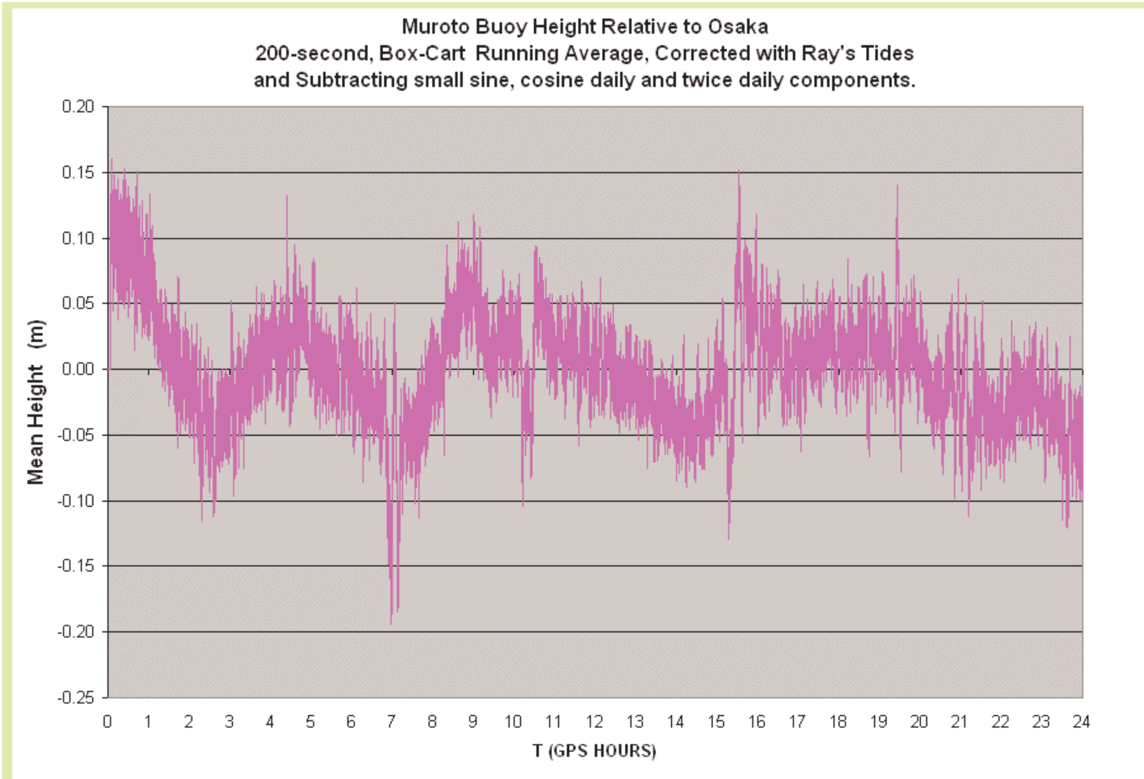

Figure 9: Moving average of height, after correction for mean offset, ocean tide, solid earth tide, and residual harmonic components.

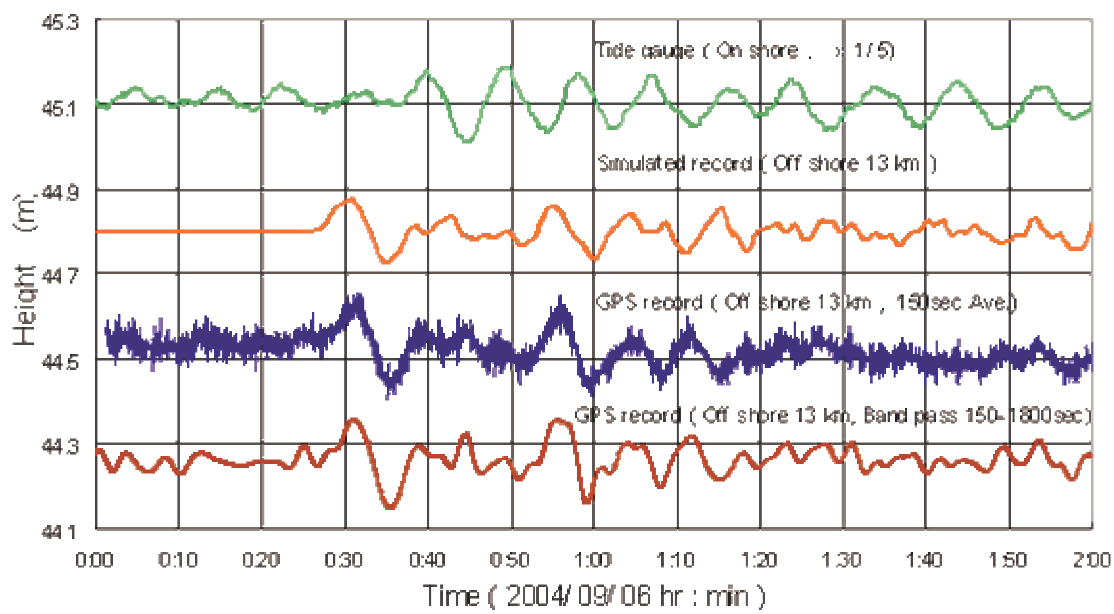

Figure 10: Tsunami waves at Muroto, following main shock off the Kii Peninsula (courtesy of Dr. Terada, Technical Research Institute, Hitachi Zosen Corporation)

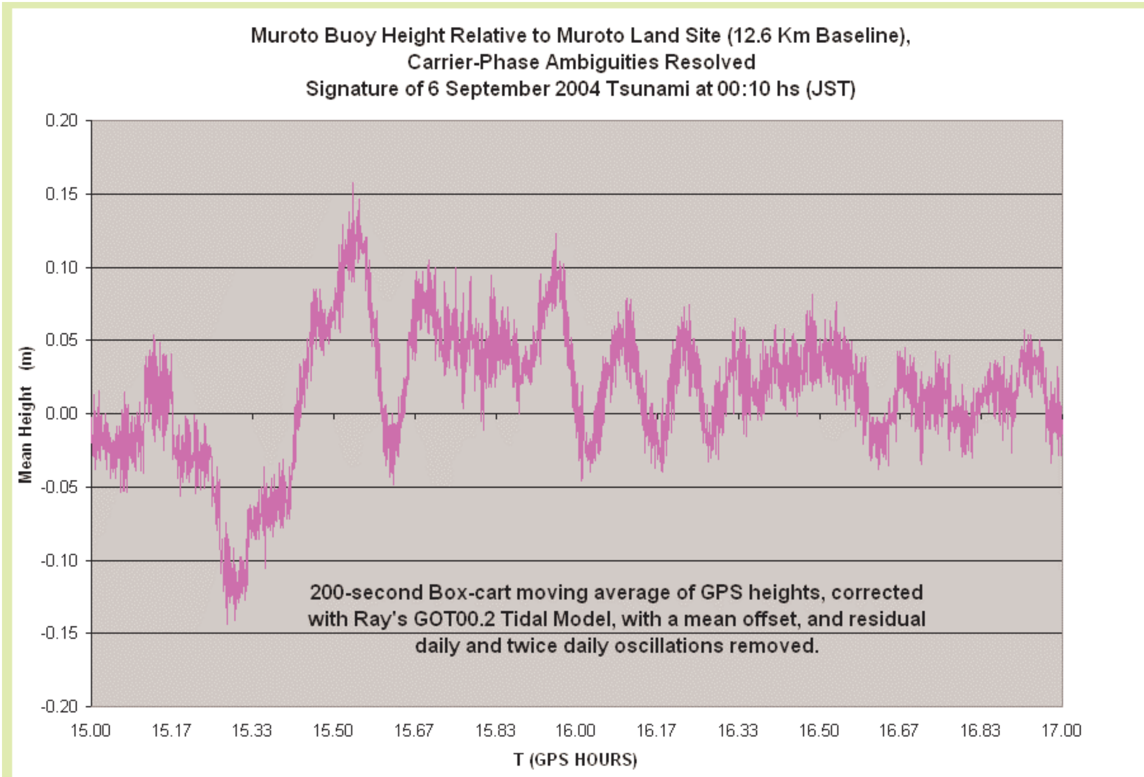

Figure 11: Tsunami signature in the mean heights of Fig. 10; reference site: Muroto.

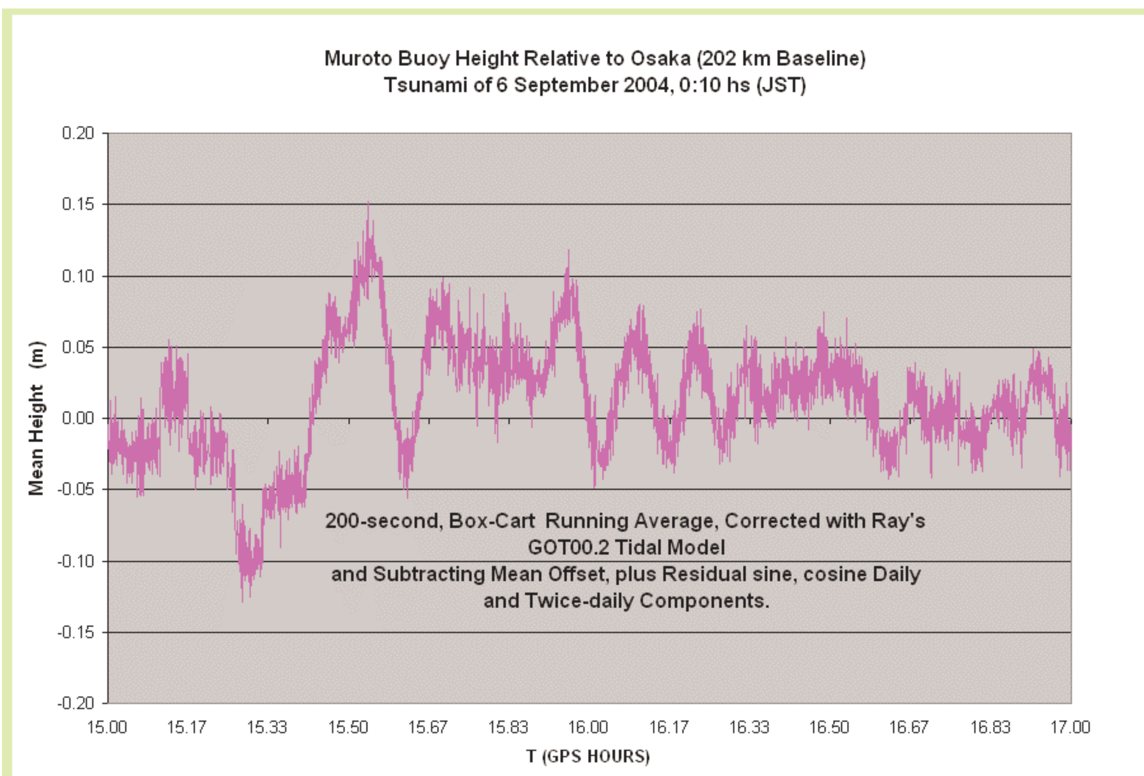

Figure 12: As in Fig. 11, but with Osaka as the reference station.

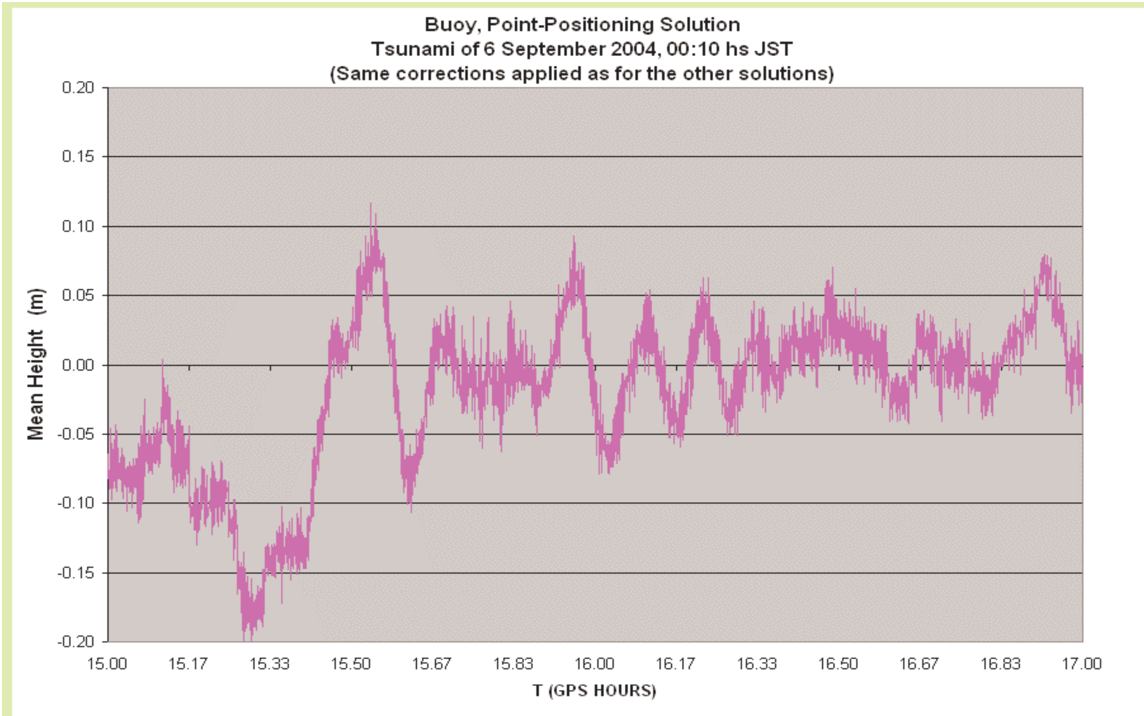

Figure 13: Point-positioning solution, using only GPS data from the buoy's receiver, with precise CODE/IGS orbits and 30-second clocks.

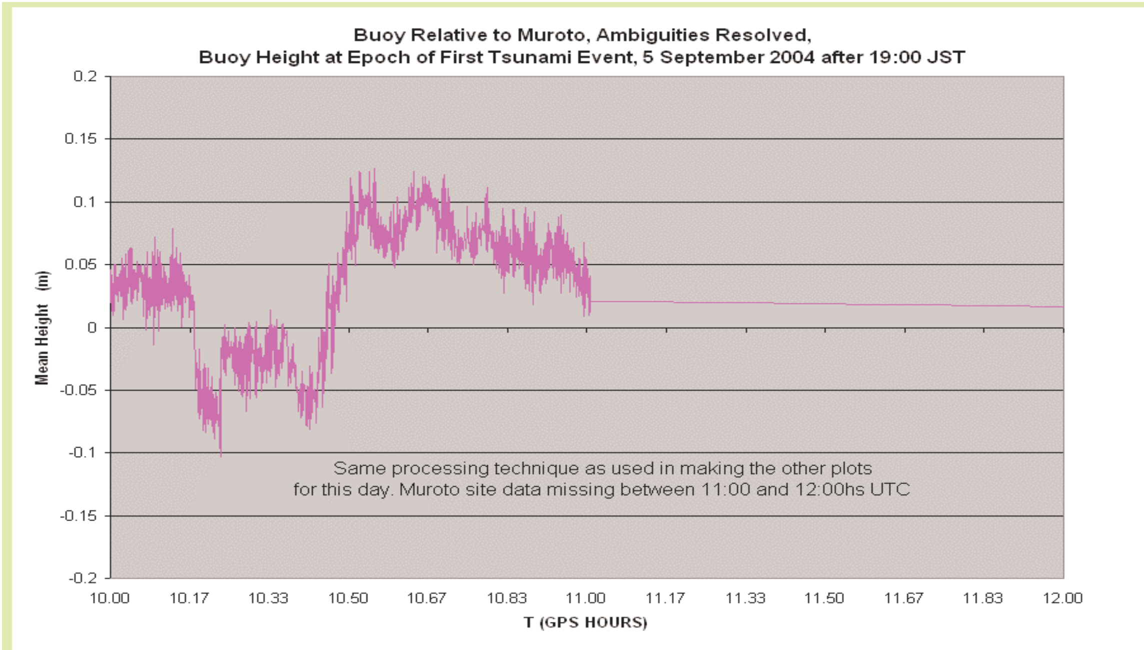

Figure 14: Possible signature of the first tsunami of 5-6 Sept. 2004 (there is a gap in the GPS data from the Muroto reference station, from just after 11:00hs, until 12:00hs UTC.)

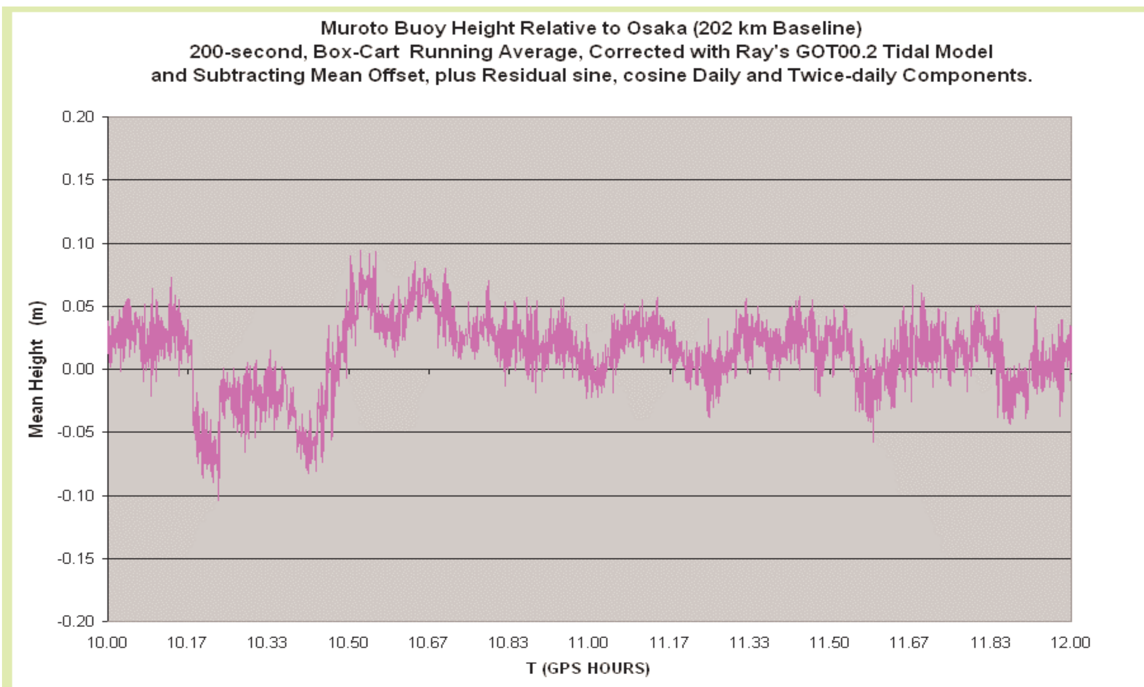

Figure 15: Same as Fig. 14, but with the reference station in Osaka, that has no gaps in its data.

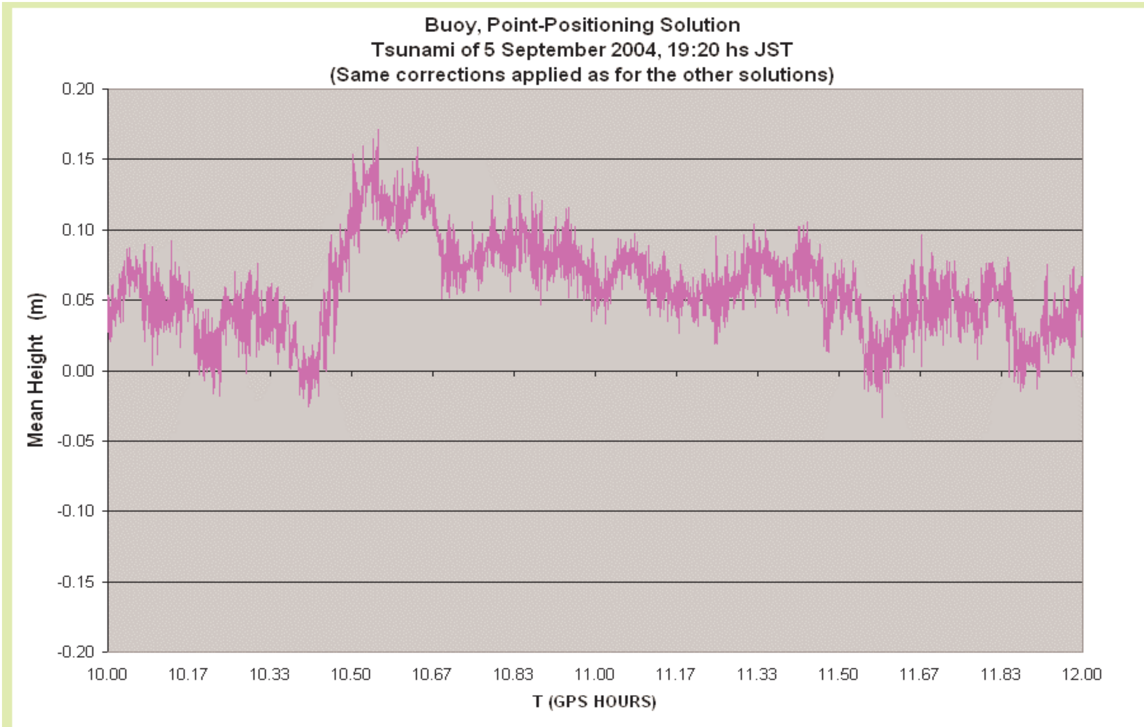

Figure 16: Same as Figs. 14 and 15, but using only data from the buoy's receiver.

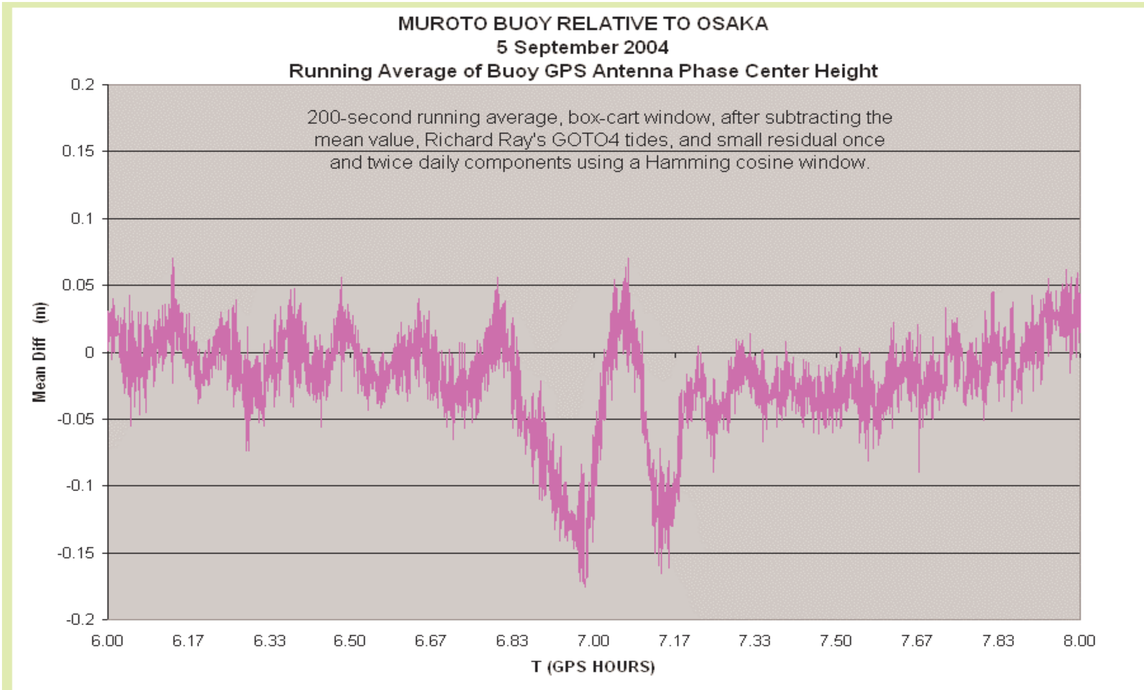

Figure 17: What could be very long period waves passing by the Muroto buoy, but not related to any reported seismic activity. This feature appears also in the point-positioning solution.

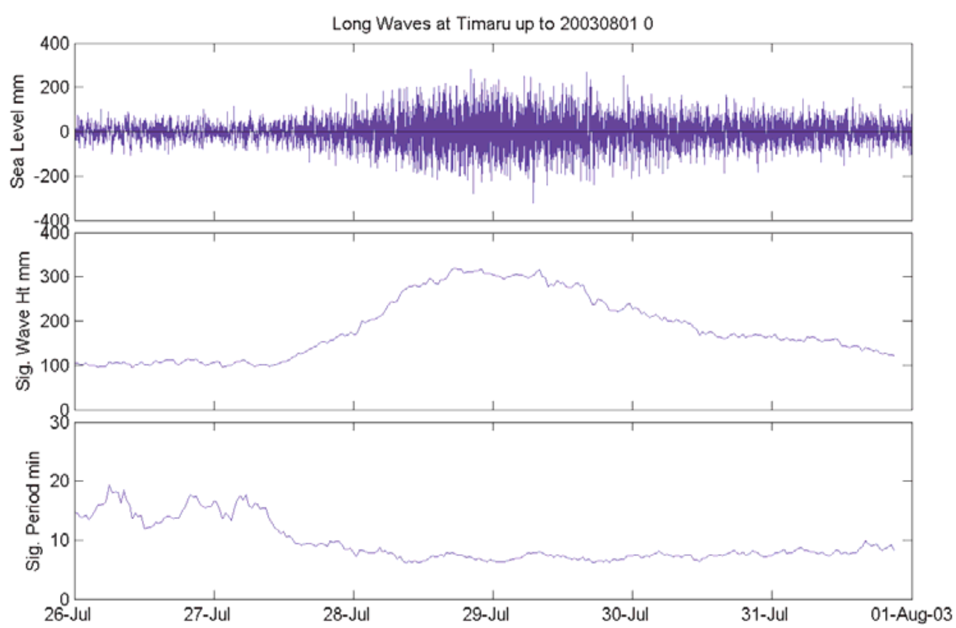

Figure 18: The feature in Fig. 17 might be caused by small long waves, often the effect of distant storms or changes in atmospheric pressure, such as these long waves at a tidal station in New Zealand; significant (mean of 1/3 highest waves) height and period, in mm and minutes (from Mulgor Ltd, http://www.mulgor.co.nz/index.html).

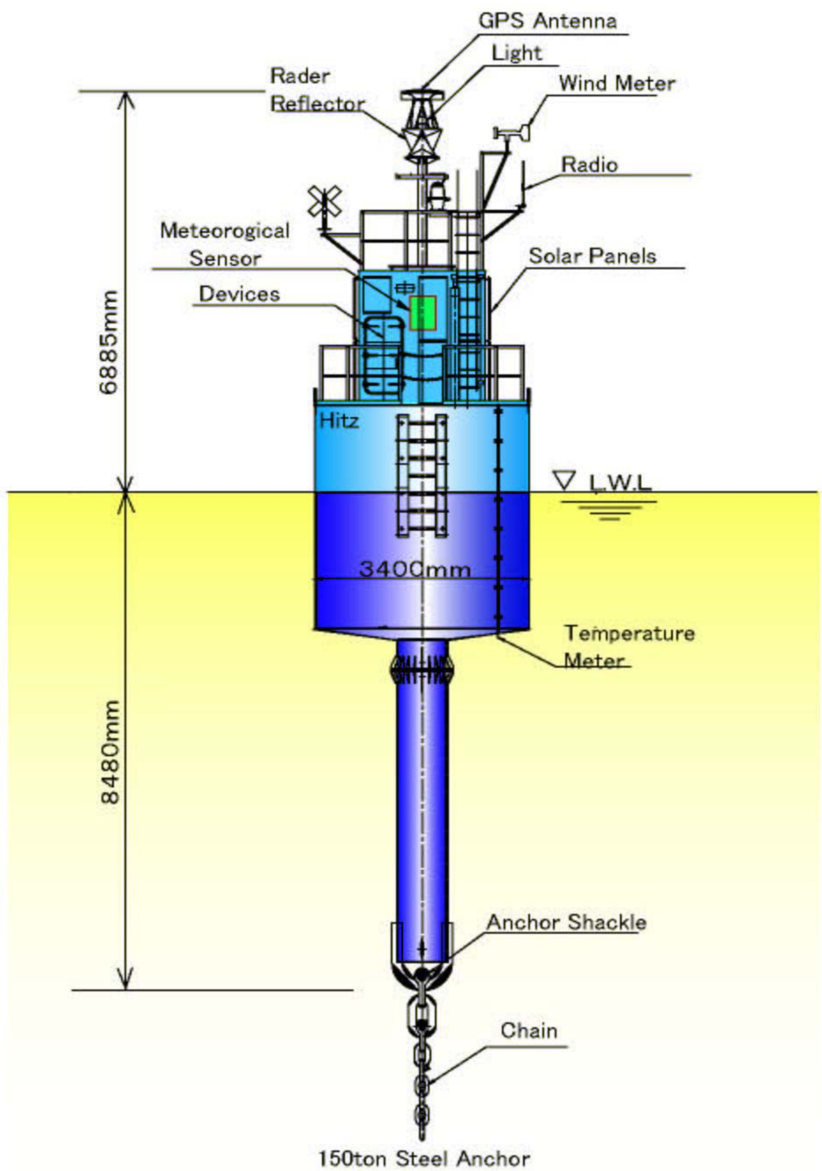

Figure 19. Schematic diagram of the GPS buoy and tsunami meter anchored off Muroto.

References:

Kato T., Y. Terada, K. Ito, R. Hattori, T. Abe, T. Miyake, S. Koshimura, T. Nagai; Tsunami due to the 2004 September 5th Off Kii Peninsula Earthquake, Japan, Recorded by a new GPS buoy, in *Earth, Planets and Space,* (in printing), 2005

Colombo O.L., A.W. Sutter, A.G. Evans: "Evaluation of Precise, Kinematic GPS Point Positioning", in *Proceedings, ION GNSS 2004*; 17th International Technical Meeting of the Satellite Division, pp. 1423-1430, 21-24 Sept. 2004, Long Beach, California.

Rabinovich A.B., F.E. Stephenson, "Longwave Measurements for the Coast of British Columbia and Improvements to the Tsunami Warning Capability", in *Natural Hazards* 32: 313–343, 2004.